

Empirical and Theoretical Dosimetry in Support of Whole Body Radio Frequency (RF) Exposure in Seated Human Volunteers at 220 MHz

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This study reports the dosimetry performed to support an experiment that measured physiological responses of seated volunteer human subjects exposed to 220 MHz fields. Exposures were performed in an anechoic chamber which was designed to provide uniform fields for frequencies of 100 MHz or greater. A vertical half-wave dipole with a 90° reflector was used to optimize the field at the subject's location. The vertically polarized E field was incident on the dorsal side of the phantoms and human volunteers. The dosimetry plan required measurement of stationary probe drift, field strengths as a function of distance, electric and magnetic field maps at 200, 225, and 250 cm from the dipole antenna, and specific absorption rate (SAR) measurements using a human phantom, as well as theoretical predictions of SAR with the finite difference time domain (FDTD) method. A NBS (National Bureau of Standards, now NIST, National Institute of Standards and Technology, Boulder, CO) 10 cm loop antenna was positioned 150 cm to the right, 100 cm above and 60 cm behind the subject (toward the transmitting antenna) and was read prior to each subject's exposure and at 5 min intervals during all RF exposures. Transmitter stability was determined by measuring plate voltage, plate current, screen voltage and grid voltage for the driver and final amplifiers before and at 5 min intervals throughout the RF exposures. These dosimetry measurements assured accurate and consistent exposures. FDTD calculations were used to determine SAR distribution in a seated human subject. This study reports the necessary dosimetry to precisely control exposure levels for studies of the physiological consequences of human volunteer exposures to 220 MHz. Bioelectromagnetics 26:440–447, 2005.

Published 2005 Wiley-Liss, Inc.[†]

Key words: resonance; E field; H field; field scans; specific absorption rate (SAR); finite difference time domain (FDTD)

INTRODUCTION

In 1994, researchers at the John B. Pierce Laboratory initiated a series of studies that involved human exposures to radio frequency (RF) energy [Adair et al., 1998, 1999a]. The purpose of these studies was to measure the basic physiological thermoregulatory responses of adult human volunteers resulting from RF exposures. Studies were completed at 450 and 2450 MHz at the John B. Pierce Laboratory and at Brooks City-Base, TX, USA [Adair et al., 1998, 1999a,b, 2000, 2001]. Recently, this experimental program was continued at 100 MHz, the resonant frequency for a seated adult human [Adair et al., 2003; Allen et al., 2003]. Exposures at 220 MHz were chosen to fill in the gap between 100 and 450 MHz. This study reports the dosimetry performed to define the exposure conditions at 220 MHz. An orderly measurement plan, similar to

the 100 MHz study, was followed to achieve accurate exposure criteria.

Several experiments were performed to define the RF fields to which human subjects were to be exposed. The experimental plan involved a series of measurements to quantify: (1) instrument drift, (2) field strengths as a function of distance, (3) electric and

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Received for review 2 June 2004; Final revision received 18 September 2004

DOI 10.1002/bem.20101
Published online 1 June 2005 in Wiley InterScience (www.interscience.wiley.com).

magnetic field maps at 200, 225, and 250 cm from the dipole antenna, and (4) specific absorption rate (SAR).

Measurement of the average SAR required the use of a tissue equivalent phantom exposed to the same field as the volunteer subjects. The tissue equivalent phantom (referred to as the "green man"), a human shaped plastic bag filled with tissue equivalent material [Olsen and Griner, 1989], provides an accurate assessment of whole body average SAR, but due to its homogeneity does not provide accurate information concerning SAR distribution. Finite difference time domain (FDTD) calculations were made to determine the distribution of the energy deposition in a standard 70 kg seated human exposed to 220 MHz fields. The FDTD modeling utilized a plane wave condition for all calculations. Thus, it was expected to predict larger SAR's than the experimental condition. The FDTD calculation used anatomically correct tissue properties that resulted in more accurate predictions of the SAR distribution than the "green man."

Field levels were monitored throughout the human tests using a NBS H field probe to monitor the field before and during each RF exposure. E and H field probes were developed at NBS, Boulder, Colorado to be used as standards for fields below 1000 MHz [Greene, 1975]. These procedures assured accurate field definition and precise exposures over the 15 months required to complete the study.

METHODS

Experimental

The 220 MHz study was performed using an Amplifier Research Model 2000 LA amplifier. The output signal was fed into a vertical half-wave dipole with a 90° corner reflector. The tests were conducted in an anechoic chamber located at Brooks City-Base, TX. All interior walls of this 6.7 × 6.7 × 9.8 m electrically shielded chamber were covered with 1.8 m pyramidal microwave absorber. Using standard engineering methods, the far field of the antenna system was calculated to be 68 cm and all human exposures were made within the 200–250 cm region, thereby assuring far field conditions.

All field measurements were made with the probe, in a vertical position for the dipole and in a 90° position for the loop antennas, attached to a three-dimensional scanner borrowed from the Naval Health Center Detachment, Brooks City-Base. Measurements were made in a normal position with both probes to assure vertical E field and horizontal H field. The scanner could remotely scan over a 100 × 100 × 200 cm volume. Measurements were made with the model

2 serial #1 NBS E field probe, and the model 2 serial #1 NBS H field probe. In the first measurement, the drift of the probe was determined with the transmitter held at 1000 W. This required leaving the probe stationary in the center of the field and measuring the drift over 11.7 min, the time required for one pass of the scanner. These measurements defined the drift error for field mapping, i.e., no field map could be made with a precision greater than these stationary drift values.

Electric field levels were measured from 180–280 cm (radiating antenna to field measuring probe) along the antenna boresight for 1000 W transmitter output power. For far field conditions, the incident power density should change as $1/R^2$, where R is the distance from the back of the corner reflector to the field-measuring probe. Minor deviations will usually be observed due to reflections in the chamber, but major deviations require further investigation to uncover the source of the deviation. The first series deviated from $1/R^2$, so a second series was run with resistive cloth covering the scanner electric motors to reduce its electromagnetic scatter; however, the deviation was still observed. The third series of measurements was made with resistive cloth covering the wires connecting the scanner motors to minimize the electromagnetic coupling to the wires.

After the $1/R^2$ measurement was successfully completed, XY-plane field maps at $Z = 200, 225$, and 250 cm were completed using the mechanical scanner described above and the NBS 10 cm dipole, and the NBS 3.2 cm loop antenna. The voltage outputs of the NBS dipole and loop antennas were converted to E (V/m) and H (A/m) field and then into power density using:

$$PD_E(\text{mW}/\text{cm}^2) = E^2/3770 \quad (1)$$

$$PD_H(\text{mW}/\text{cm}^2) = 37.7H^2 \quad (2)$$

All data were transferred into Microsoft Excel for storage and analysis. The Excel cells corresponding to the shape of the human at 225 cm were averaged to obtain the incident power density for a 1000 W exposure. The average of the power density over this area was divided by 1000 to obtain power density per Watt of forward power, and this factor was divided into the desired incident power density to determine the desired transmitter power for each designated incident power density.

Phantom "Green Man" SAR Measurements

SAR was measured using a "green man," a human shaped plastic bag filled with tissue equivalent material, seated in the subject's chair with the centerline of the

1000 W for the duration of the field mapping. Thus, most of the NBS probe drift can be accounted for by the drift in transmitter output.

The measurement of power density with the NBS dipole as a function of distance from the radiating dipole is shown in Figure 1. The maximum deviation from $1/R^2$ noted at 260 cm was 15%. The deviation across the exposure plane, 200–250 cm was $\pm 7\%$. This result was probably primarily due to reflections from the back wall. The agreement is within the precision expected on the basis of $1/R^2$.

The electric field map at 225 cm (Fig. 2), taken with the NBS 10 cm dipole, reveals a uniform vertical E field over the trunk of the subject. However, the center of the field is 15 cm above the beam geometric center, probably due to the fact that the absorber cones in the floor of the chamber were closer to the beam geometric center (60 cm) than the absorbers in the ceiling (125 cm). The 10 cm dipole was used to measure the power density at the feet, which was 0.51 times that measured at the center field position.

The NBS 3.2 cm diameter H field probe map taken at 225 cm (Fig. 3) indicates the H field was located on the beam geometric center, 105 cm above the floor. These results are probably due to the lack of interaction of the magnetic field with the chamber absorber. Each point on the E field map was divided by the corresponding point on the H field map and the results plotted as a map of the field impedance (Fig. 4). The minimum field impedance over the 225 cm plane was 317 Ω , the maximum was 391 Ω , and the mean value

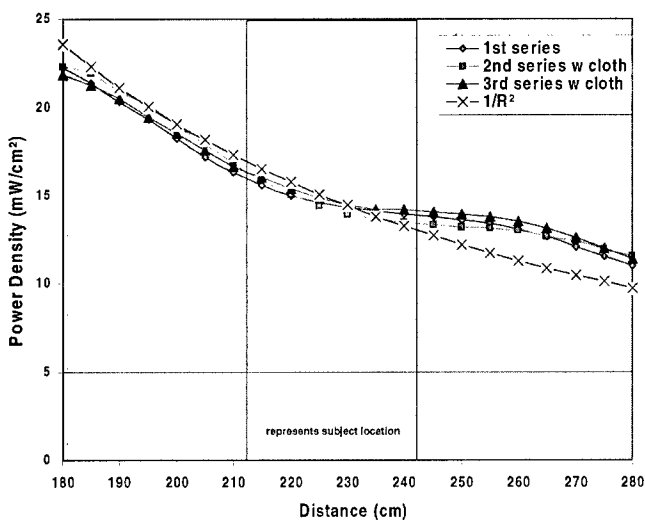


Fig. 1. Centerline scan from 180 to 280 cm along the antenna bore-sight made with a NBS dipole antenna. $1/R^2$ calculations are normalized to the 230 cm point for comparison. [The color figure for this article is available online at www.interscience.wiley.com.]

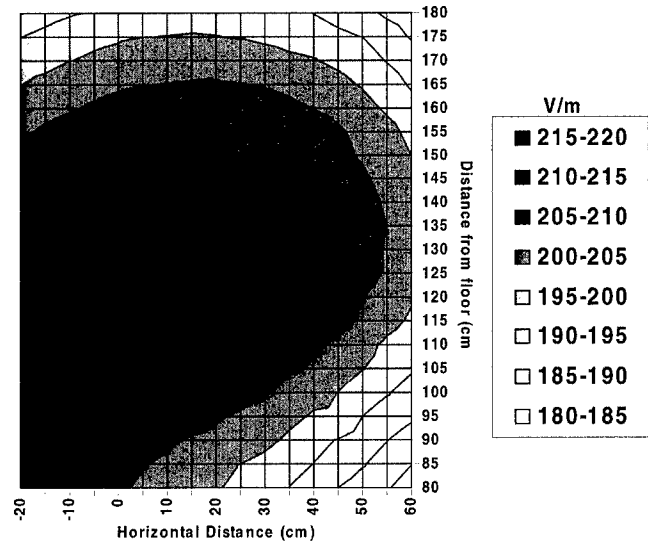


Fig. 2. Plot of the electric field intensity V/m across the 225 cm plane, radiating antenna to field map position. The model 2, serial #1 NBS 10 cm dipole was used to map the field. Measurements were made for 1000 W transmitter output power. [The color figure for this article is available online at www.interscience.wiley.com.]

was 347 Ω comparing favorably, within 9%, with the free space impedance of 377 Ω .

To determine the exposure incident power density, the NBS 10 cm dipole E field map was converted to an incident power density using Equation 1. The outline of a standard 70 kg man was superimposed over the 225 cm, two-dimensional incident power density map

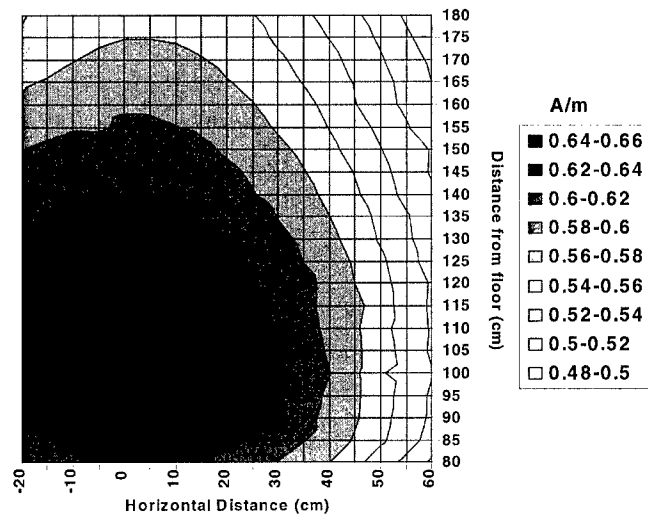


Fig. 3. Plot of the magnetic field intensity A/m across the 225 cm plane, radiating antenna to field map position. The model 2, serial #1 NBS 3.16 cm loop antenna was used to map the field. Measurements were made for 1000 W transmitter output power. [The color figure for this article is available online at www.interscience.wiley.com.]

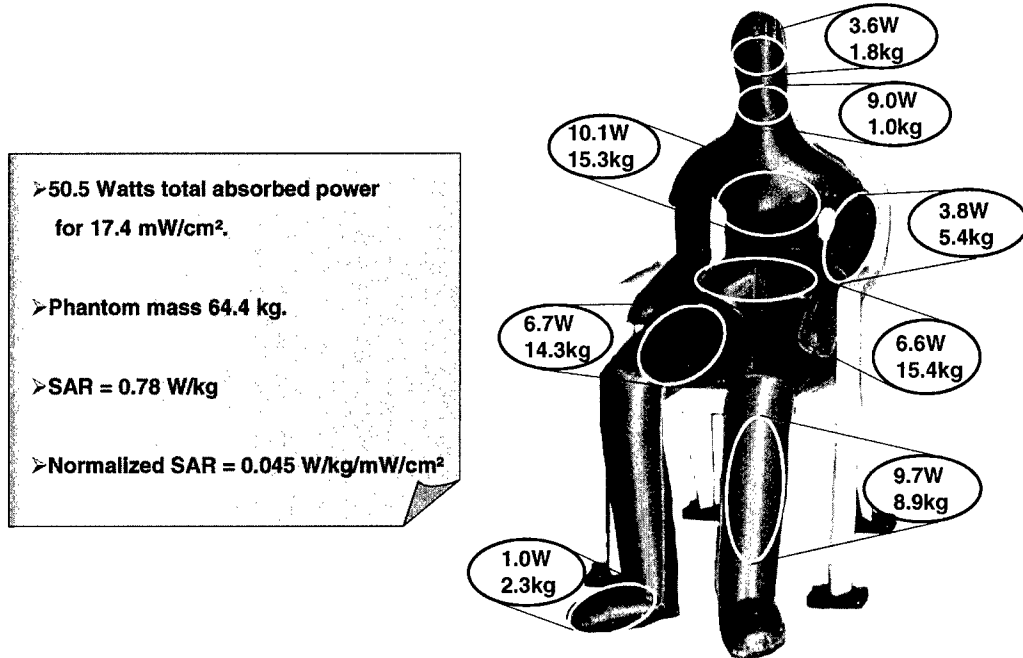


Fig. 6. SAR measurements in the seated "green man" phantom. Measurements were made for 1500 W transmitter output power. The masses of specific areas were measured and these masses as well as the total power (W) absorbed in each area are noted in the oval for each area. The mass of the arm, leg, and foot was determined by weighing one side and, using symmetry, multiplying this value by 2. [The color figure for this article is available online at www.interscience.wiley.com.]

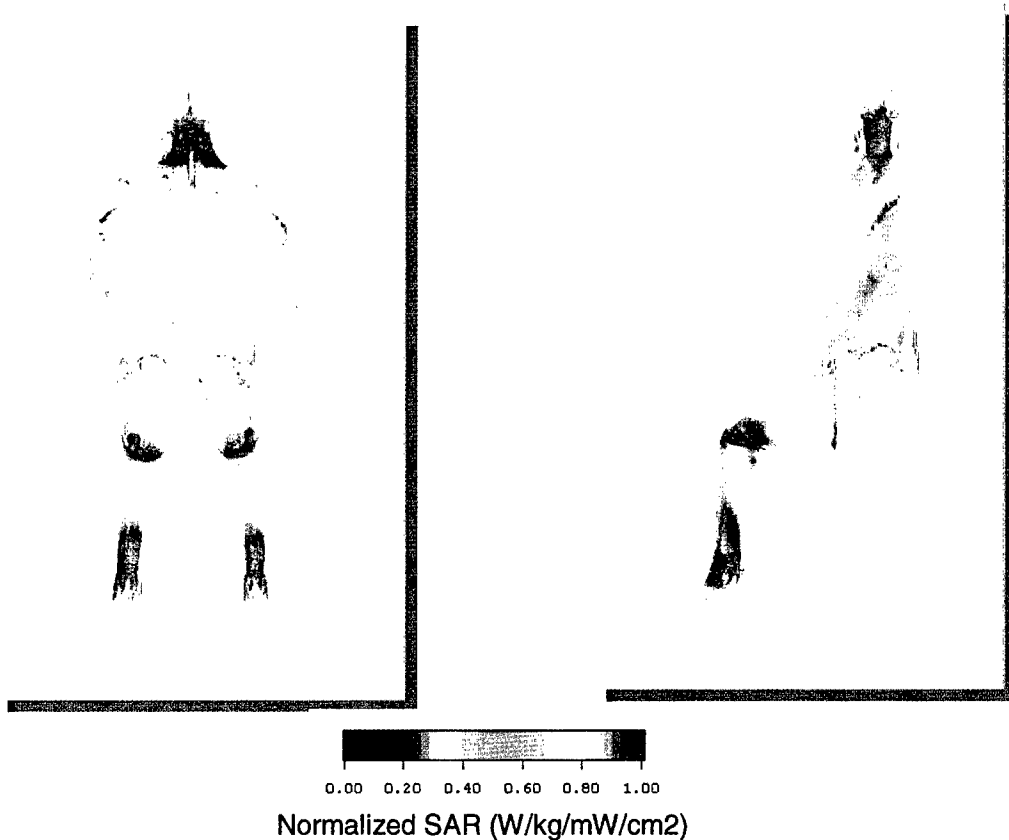


Fig. 7. SAR distribution in the 70 kg seated human model. The FDTD technique was used for these calculations utilizing a cell size of 1.75 mm. Note high SAR in lower leg and ankle.

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REPORT DOCUMENTATION PAGE

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1. REPORT DATE (DD-MM-YYYY) September 2005			2. REPORT TYPE Journal Article		3. DATES COVERED (From - To) March 2004 - September 2005	
4. TITLE AND SUBTITLE Empirical and Theoretical Dosimetry in Support of Whole Body Radio Frequency (RF) Exposure in Seated Human Volunteers at 220 MHz					5a. CONTRACT NUMBER F41624-01-C-7002	
					5b. GRANT NUMBER N/A	
					5c. PROGRAM ELEMENT NUMBER 62202F	
6. AUTHORS Stewart J. Allen, Eleanor R. Adair, Kevin S. Mylacraine, William Hurt and John Ziriaux					5d. PROJECT NUMBER 7757	
					5e. TASK NUMBER B3	
					5f. WORK UNIT NUMBER 47	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Advanced Information Engineering Services A GENERAL DYNAMICS COMPANY & AFRL 3276 Reliance Loop Brooks City-Base, TX 78235					8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Human Effectiveness Directorate, Directed Energy Bioeffects Division, Radio Frequency Radiation Branch 3276 Reliance Loop Brooks City-Base, Texas 78235					10. SPONSOR/MONITOR'S ACRONYM(S) AFRL, HE	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-HE-BR-JA-2004-0011	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.						
13. SUPPLEMENTARY NOTES AFRL Contract Monitor: Lt Jacque Garcia, (210)-536-2685						
14. ABSTRACT This paper reports the dosimetry performed to support an experiment that measured physiological responses of seated volunteer human subjects exposed to 220 MHz fields. Exposures were performed in an anechoic chamber which was designed to provide uniform fields for frequencies of 100 MHz or greater. These dosimetry measurements assured accurate and consistent exposures. FDTD calculations were used to determine SAR distribution in a seated human subject. This paper reports the necessary dosimetry to precisely control exposure levels for studies of the physiological consequences of human volunteer exposures to 220 MHz.						
15. SUBJECT TERMS resonance; E field; H field; field scans; specific absorption rate (SAR); finite difference time domain (FDTD)						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON Lt Jacque Garcia	
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) (210) 536-2685	